

# Two-Phase Behavior in Microgravity

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Thermal and Fluids Analysis Workshop

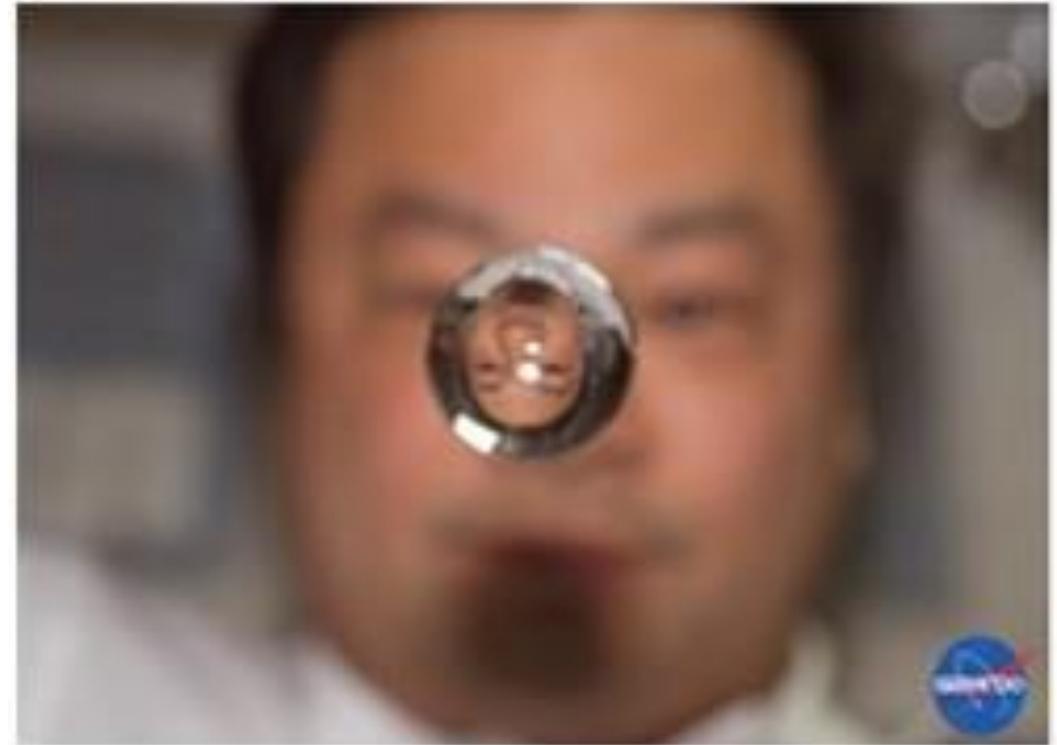
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# Introduction

- The behavior of liquid and vapor/gas two-phase mixtures in microgravity often surprises us
- Two million years of evolution on planet Earth has equipped us well for a 1-g world:
  - Rain falls as small drops, drips off leaves, and falls to the ground where it can sit as a puddle or be absorbed
- We have difficulty thinking about what happens in an environment where liquid drops are static and can grow to large size - our intuition fails us

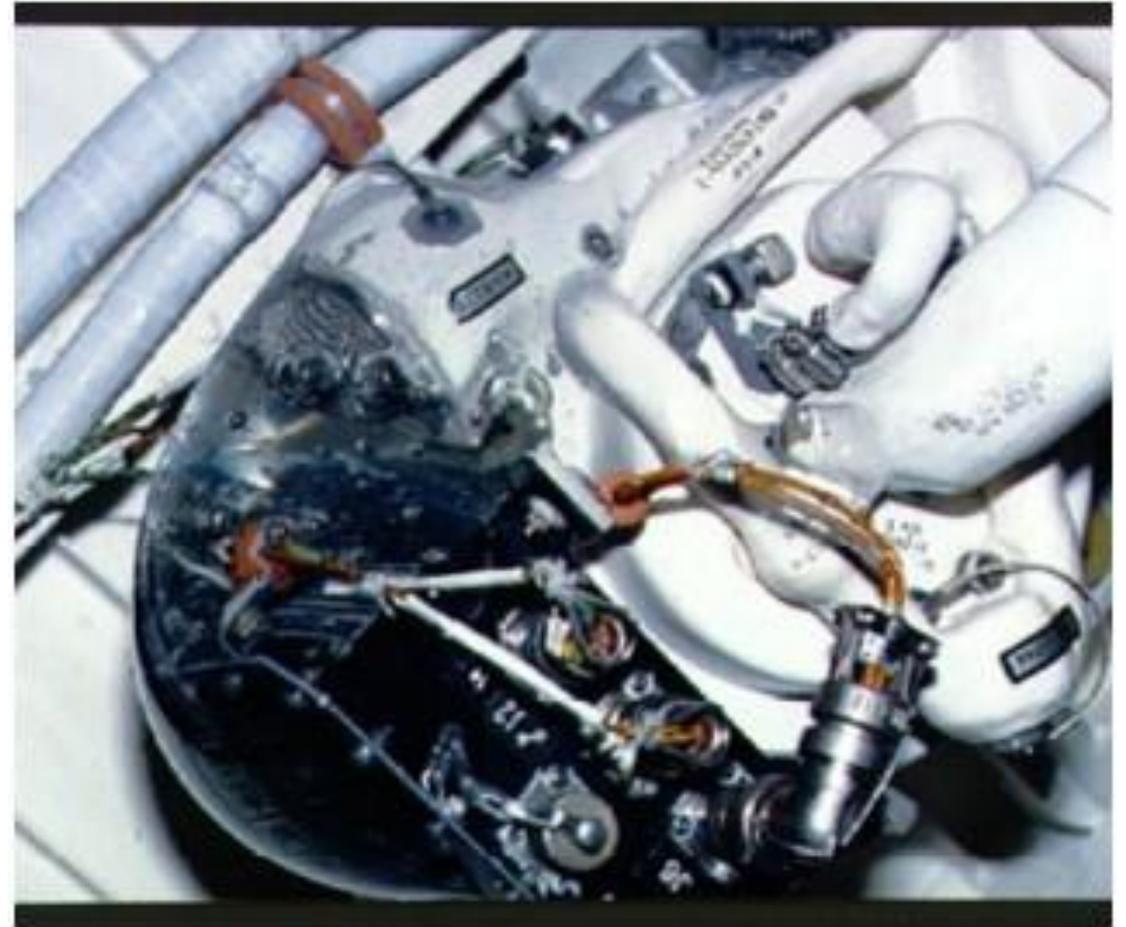
# Unique Microgravity Two-Phase Behavior

- Some two-phase behavior is seen only in microgravity
- The large free-floating drop seen here will grow in a spherical shape as liquid is added
- On the ground, large spherical drops cannot exist



# Unique Microgravity Two-Phase Behavior

- Water carryover at the Space Shuttle Orbiter Humidity Separator formed as a large volume of water on STS-32
- The separator divided an air/condensate flow stream using centrifugal force
- On this mission, the separator pitot became clogged with debris and several liters of condensate overflowed and enveloped the outside of the unit



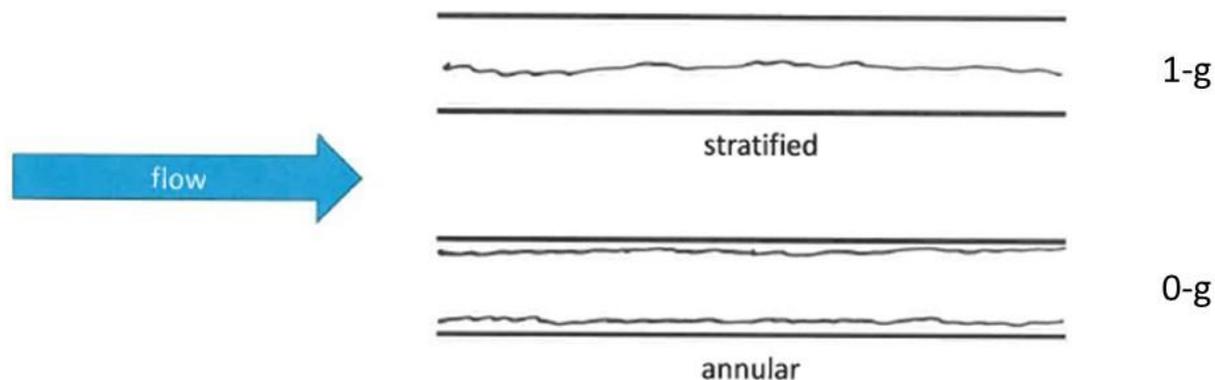
# Unique Microgravity Two-Phase Behavior

- Liquid on a surface in 0-g can be surprisingly difficult to move
- On a 2013 EVA from the International Space Station, water carryover from a plugged EMU air/condensate separator resulted in the addition of water to the vent loop that empties into the EMU helmet
- Over time, the water built up in the helmet of spacewalking astronaut Luca Parmitano
- The water was virtually static inside the helmet despite the presence of airflow venting into the rear of the helmet
- The water in the helmet did not move because the airflow drag did not exceed the surface tension forces holding the water in place



# Microgravity Two-Phase Behavior

- When liquid and gas (or vapor) flow in a horizontal pipe in 1-g, at some flow conditions\* the flow is stratified
  - The liquid flows along the bottom of the tube and the gas flows along the top
- At the same conditions in 0-g, the liquid would cover the entire inner surface of the tube the gas would flow down the center of the liquid annulus
  - The absence of gravity completely changes the governing physics and the resulting flow behavior
- On Earth, gravity is often the dominant factor in the physics of two-phase systems
- When the acceleration of gravity is removed, another force will become dominant and the physics can change dramatically



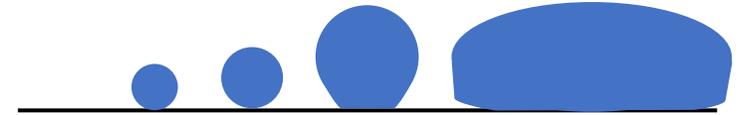
\*Pipe diameter, liquid and gas components, temperature, pressure, and liquid and gas flow rates

# Two-Phase Fluid Physics

- Our 1-g experience with two-phase flows have limited application to microgravity
- But careful observation, physical understanding, calculations and tests go a long way towards allowing us to successfully predict 0-g fluid behavior

# Drops on Surfaces

- Let's begin with the simplest case of a static fluid
- A water droplet on Earth will rest on a surface
- If the surface is fully hydrophobic and the drop's diameter is 1 mm or less, it will be virtually spherical since the surface tension forces are much larger than the buoyancy forces
- If water is added to the drop, it will grow in diameter and height until a critical elevation is reached where the hydrostatic pressure at the bottom of the drop is balanced by the fluid surface tension



- A surface is considered to be hydrophobic if the fluid has a contact angle (the angle between the liquid/vapor interface and the solid surface) greater than  $90^\circ$
- This causes the fluid to bead up on the surface
- A Teflon surface is hydrophobic and has a contact angle with water of approximately  $110^\circ$
- A fully hydrophobic surface would have a contact angle of  $180^\circ$  and a water drop would sit on the surface without wetting it

# Drops on Surfaces

- The critical drop height is derived from the Bond number, a ratio of surface tension forces to buoyancy forces
- The drop height,  $h$ , must satisfy the inequality:

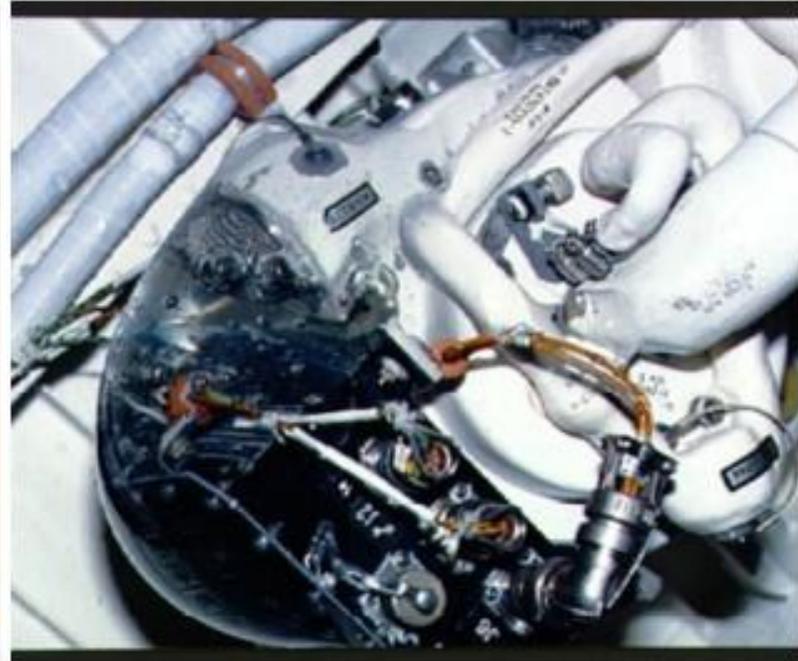
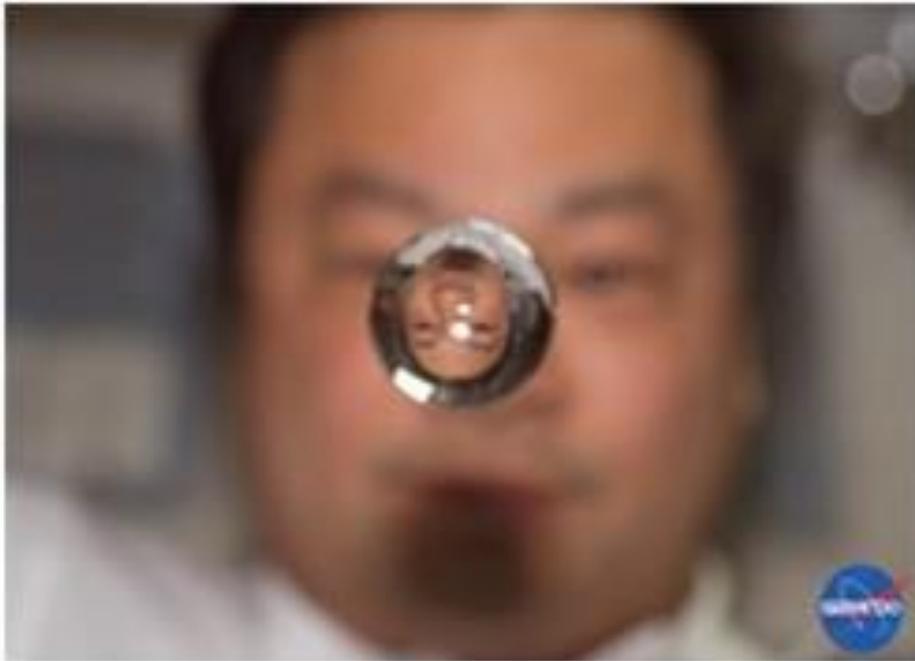
$$h \leq 2 \sqrt{\frac{\sigma}{g(\rho_f - \rho_g)}}$$

- where  $\sigma$  is the surface tension of the fluid,  $g$  is the acceleration of gravity, and  $\rho_f$  and  $\rho_g$  are the liquid and gas phase densities, respectively
- Solving the equation using water and air properties at ambient conditions gives a 1-g height limit of 5.4 mm (0.21 inches)

$$Bo = \frac{g L^2 (\rho_f - \rho_g)}{\sigma}$$

# Drops on Surfaces

- A stationary water drop in 1-g cannot be taller than 5.4 mm, but a free-floating drop in microgravity has no such constraints
- In 0-g, even large static water drops and bubbles will be spherical in the absence of an enclosure or external forces



# Movement of a Wall-Bound Liquid Drop in a Free-Stream Flow

- There are numerous studies in the literature regarding co-current gas and liquid two-phase flows in microgravity
- These studies are characterized as internal flows
- These flows are characteristic of situations where the volumetric flow rates of liquid and vapor are of the same order of magnitude
- Often, we must assess situations where we have little volumetric liquid flow
  - Perhaps because the liquid flow is unwanted or because its presence is outside of the planned-for system performance
- The example of water in the EMU helmet, while technically an internal flow, is better characterized as an external flow – the reaction of liquid on a surface to freestream airflow
- This case is outside of the range of published 0-g two-phase studies but can be assessed using physics-based techniques

# Movement of a Wall-Bound Liquid Drop in a Free-Stream Flow

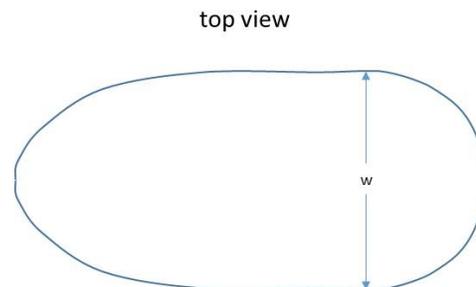
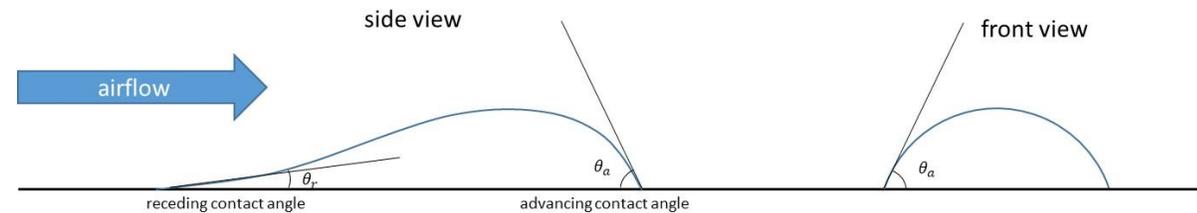
- When assessing liquid movement, it is often useful to think in terms of the static case
- We consider the liquid to be static but to be on the verge of movement, then we calculate the forces on the liquid to evaluate if they are sufficient to create movement
- Using airflow to move drops on a surface is much more difficult than you might think
- Next time you are driving in a light rain, take a look at the drops at the top of the windshield outside of the sweep of the wipers
- These drops are surprisingly stable – even at speed
  - Drops of about 2 mm in width will be stable at speeds exceeding 40 mph (18 m/s)

# Movement of a Wall-Bound Liquid Drop in a Free-Stream Flow

- Three forces act on wall-bound drops:
  - retarding force owing to surface tension
  - retarding force owing to gravity
  - drag owing to airflow
- We will look at them in turn

# Surface Tension Force

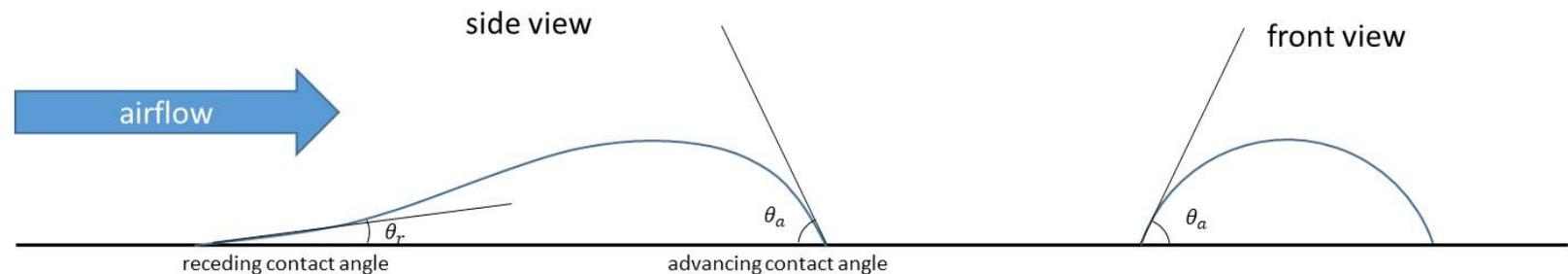
- At the onset of movement, a drop will look much like the sketch below
  - The drop has a tail at the upstream side and a sharper curvature at the downstream side of the airflow
- The difference in shape is affected by the airflow but the main cause is the difference between advancing and receding contact angles



Drop with  
Impending Movement

# Surface Tension Force

- The advancing contact angle,  $\theta_a$ , is the angle an advancing liquid makes as it moves onto a previously dry surface
- The receding contact angle,  $\theta_r$ , is the angle that the liquid makes as it is being pulled from a wetted surface
- For most fluid/surface combinations the receding contact angle is smaller than the advancing contact angle
- For water on a clean glass surface, the advancing and receding contact angles are approximately  $60^\circ$  and  $15^\circ$  respectively
- It is this difference that opposes drop movement



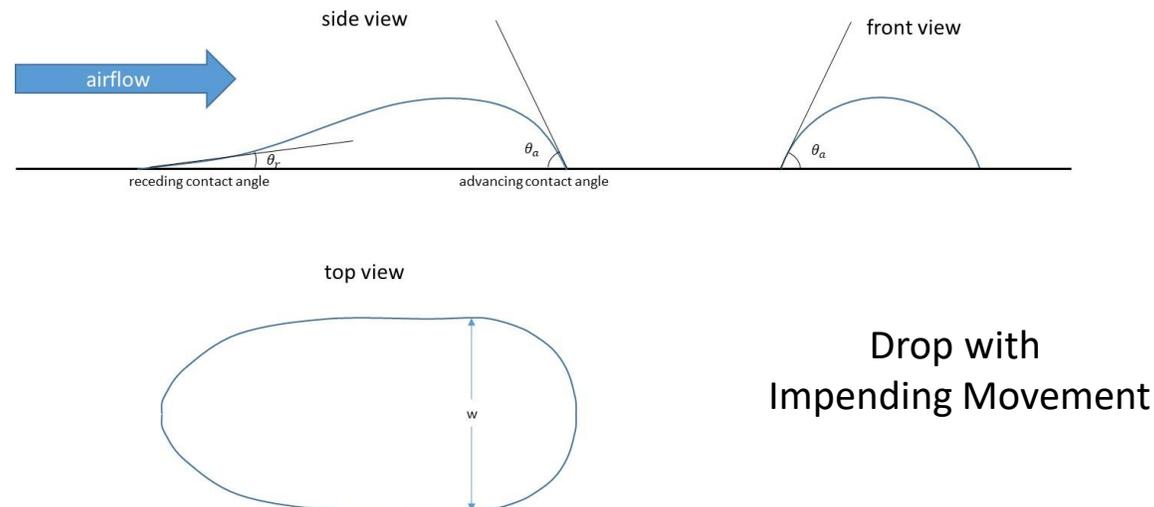
# Surface Tension Force

- The retarding force on the droplet owing to surface tension,  $F_{st}$ , can be approximated as

$$F_{st} = \sigma w \cos(\theta_r) - \sigma w \cos(\theta_a)$$

where  $w$  is the drop width and  $\theta_a$  and  $\theta_r$  are the advancing and receding contact angles, respectively

- For a 2 mm wide drop at 20°C, this retarding force is  $6.8 \times 10^{-5}$  N ( $2.4 \times 10^{-4}$  oz)
- about the weight of 1 ½ grains of sand



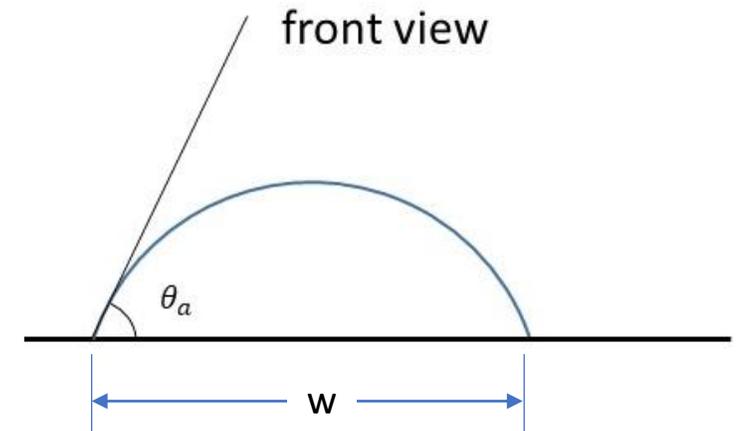
# Gravitational Force

- We can approximate the volume of the drop as the volume of the segment of a sphere with the cross section shown in the figure front view
- The radius of the sphere,  $R$ , is

$$R = \frac{w/2}{\sin \theta_a}$$

- And the volume,  $V$  is

$$V = \frac{1}{3} \pi (R - R \cos \theta_a)^2 (2R - R \cos \theta_a)$$



# Gravitational Force

- For our 2.0 mm wide drop with an advancing contact angle of  $60^\circ$ , the radius is 1.15 mm and the volume is 0.0010 cc
- The mass is 0.0010 grams
- The gravitational force that retards the drop movement will be the component in the direction parallel to the windshield
- For a windshield whose angle to the horizontal is  $25^\circ$ , this cosine effect results in a multiplier of 0.42 and a retarding force of  $F_g = 4.2 \times 10^{-6}$  N, less than 1/10th of the surface tension drag ( $F_{st} = 6.8 \times 10^{-5}$  N)
- The sum of the retarding forces is  $7.2 \times 10^{-5}$  N

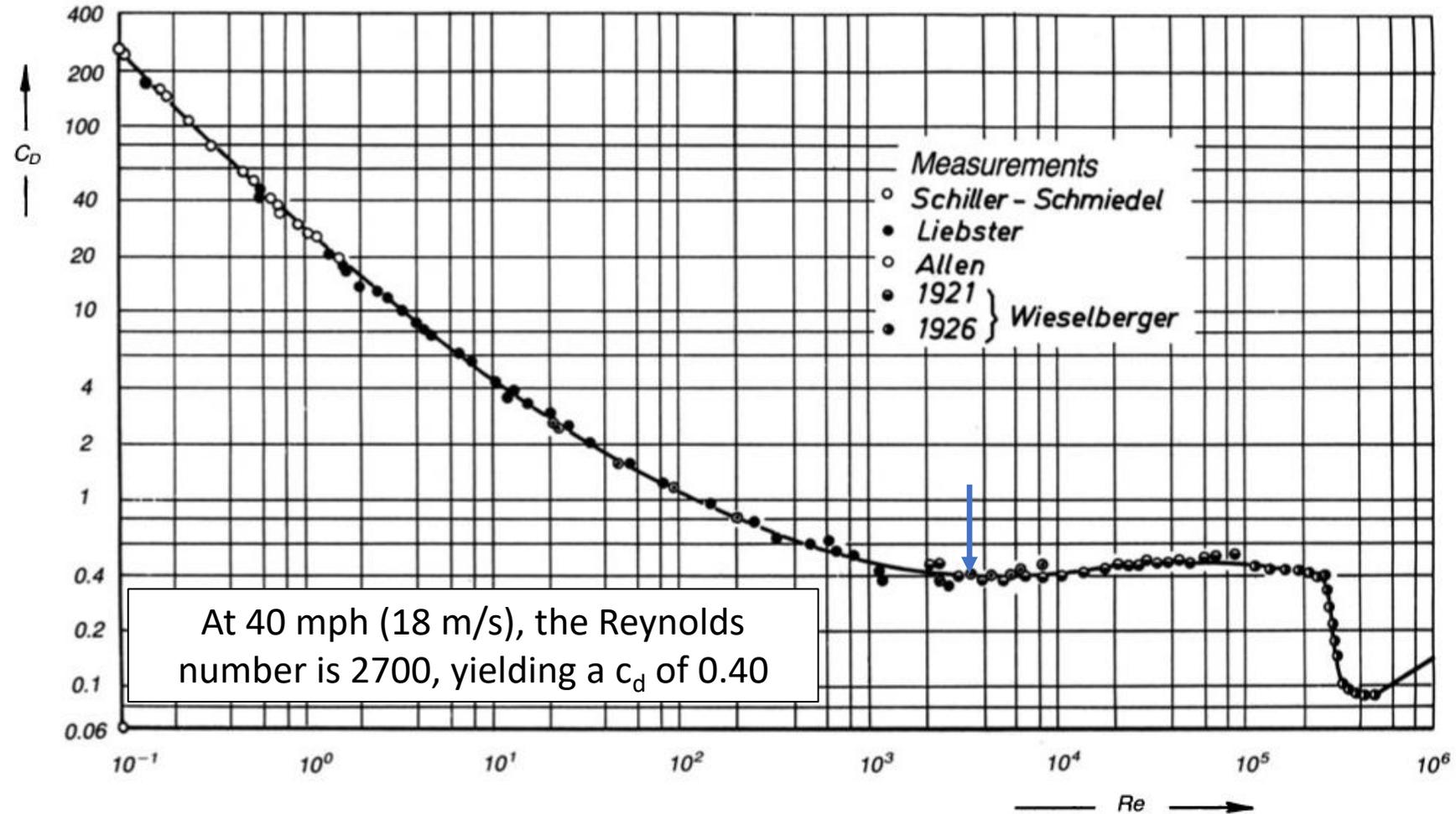
# Drag

- The drag on the drop,  $F_d$ , is calculated from

$$F_d = c_d A \frac{1}{2} \rho u^2$$

- where  $c_d$  is the drag coefficient,  $A$  is the cross-sectional area and  $\rho$  and  $u$  are the density and velocity of the airflow, respectively
- We use the drag coefficient for a sphere and take the vehicle velocity as the free-stream velocity

# Drag on a Sphere



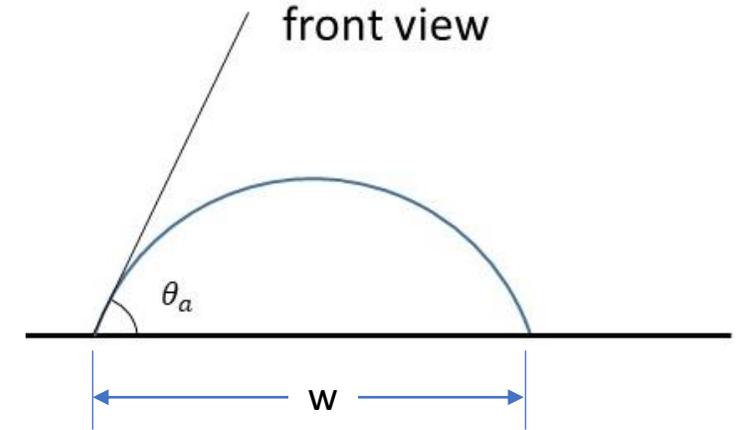
from: H. Schlichting, Boundary Layer Theory, McGraw-Hill; 2nd Edition

# Drag

- The cross-sectional area of the drop is  $0.82 \text{ mm}^2$

$$A = \frac{1}{2} R^2 \left\{ 2 \sin^{-1} \left( \frac{w}{2R} \right) - \sin \left[ 2 \sin^{-1} \left( \frac{w}{2R} \right) \right] \right\}$$

- The resulting drag force is  $6.9 \times 10^{-5} \text{ N}$  – less than the  $7.2 \times 10^{-5} \text{ N}$  of retarding force
- The 2 mm wide drop at 40 mph (18 m/s) is stable



$$F_d = c_d A \frac{1}{2} \rho u^2$$

# Movement of a Wall-Bound Liquid Drop in a Duct

- A similar analysis can be performed for a liquid drop in an air duct
- Consider a 25 mm diameter glass tube with 10 m/s of airflow at ambient conditions
- What is the maximum size water drop that will be stationary on the wall in 0-g?
- Here only surface tension force and air drag act on the liquid
- The surface tension retarding force is calculated using previous technique with the same contact angles

# Movement of a Wall-Bound Liquid Drop in a Duct

- The drag on the drop can be calculated in two ways:
  - using the form drag as previously,
  - using the drag owing to shear
- The drag from shear is calculated using the wall shear,  $\tau$
- A force balance allows the wall shear to be calculated from the pressure gradient,  $dp/dz$ ,

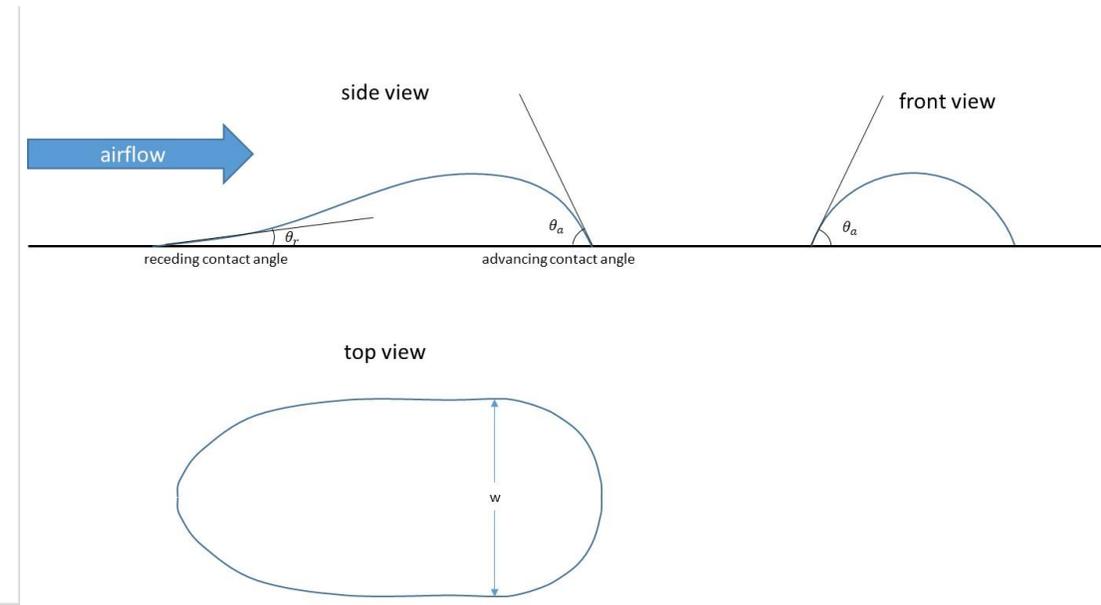
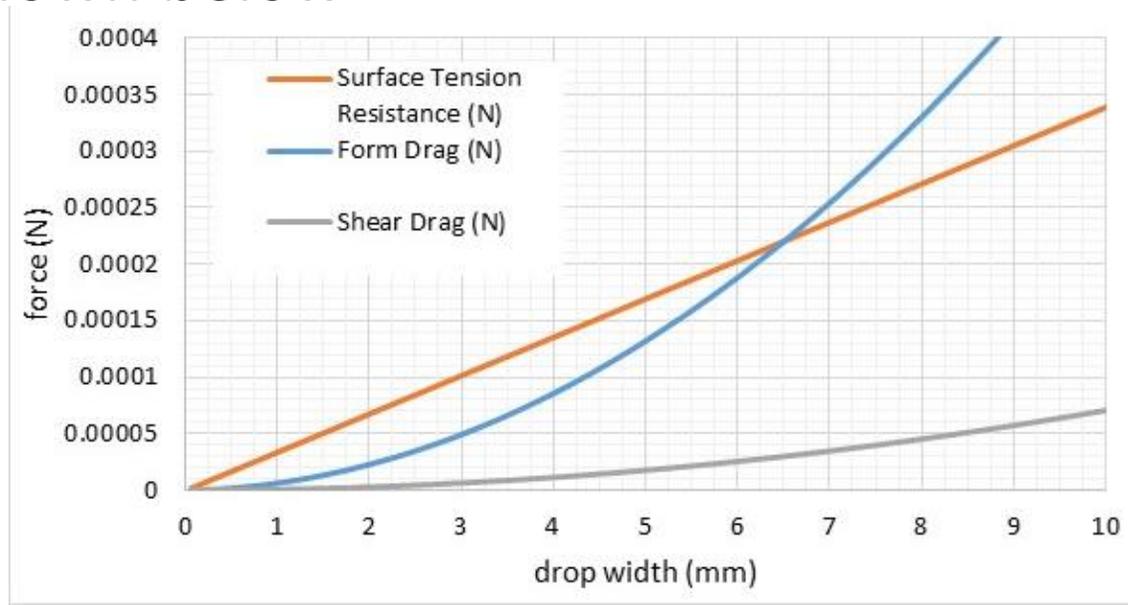
$$\tau = \frac{d}{4} \frac{dp}{dz}$$

where  $d$  is the tube diameter

# Movement of a Wall-Bound Liquid Drop in a Duct

- The pressure drop is calculated using standard techniques
- The shear drag is calculated by multiplying the wall shear by the surface area of the drop – which is approximated as  $w^2 (\pi/4+1)$
- The magnitudes of the three forces as a function of drop width are shown below

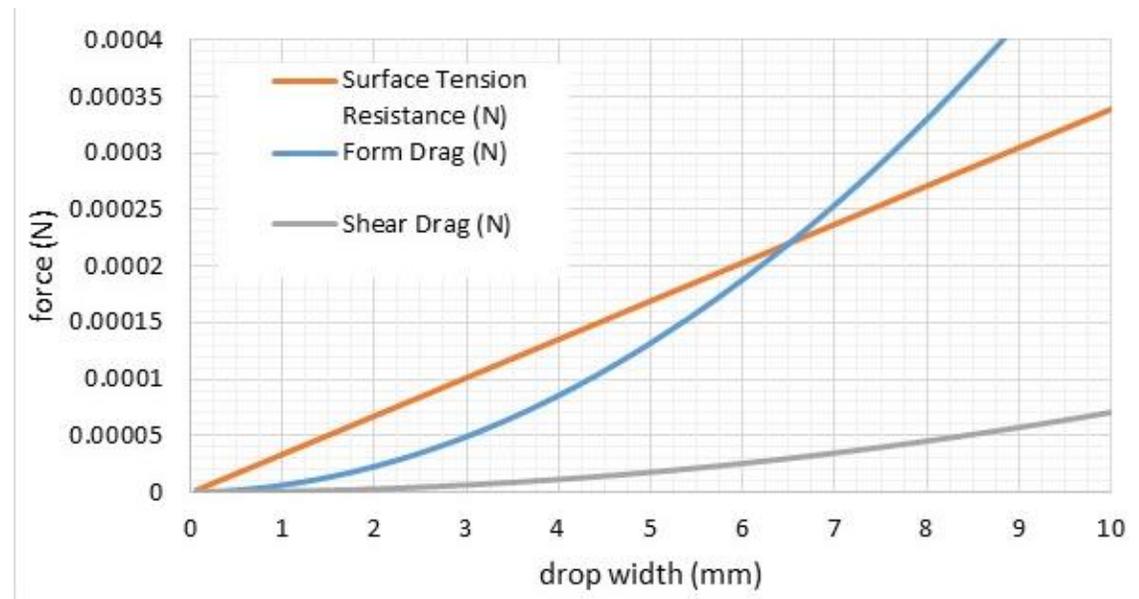
Forces on a Drop in a Pipe with Impending Movement



# Movement of a Wall-Bound Liquid Drop in a Duct

- The shear drag is an order of magnitude less than the form drag - the form drag dominates and the drag from shear can be neglected
- The graph shows that the drag and surface tension forces are in balance for a drop width of 6.5 mm (0.25 inches)
- A drop wider than 6.5 mm will move in a 10 m/s airflow while a smaller drop will not

Forces on a Drop in a Pipe with Impending Movement



Questions?

# The SHARE Heat Pipe – a Lesson in 0-g Capillarity

- In the early development of what was to become the International Space Station, the radiators for the external active thermal control system included heat pipes
- Using heat pipes would have provided segmentation of the radiator and mitigated the effects of anticipated micrometeoroid and orbital debris impacts
- Owing to the large size of the radiator array and resulting high heat transport requirement, an advanced high performance heat pipe concept was developed

# The SHARE Heat Pipe

- Traditional axial groove heat pipes are grooved tubes (constant conductance heat pipes)
- The central channel is the vapor passage and the surrounding grooves provide capillary pumping and liquid transport
  - The liquid pressure drop is the typical limiting factor – balance between pumping capability and flow resistance
- The advanced arterial heat pipe would have separate passages for the liquid and vapor
- The physical separation of the passages and the large liquid channel would provide an order of magnitude higher heat transport capability than axial groove heat pipes



from: J. Ku, Heat Pipe mini-course, 2015 Thermal and Fluids Analysis Workshop, Silver Springs MD

# The SHARE Heat Pipe

- The arterial heat pipe contained:
  - a liquid artery 10.1 mm (0.40 inch) in diameter,
  - a parallel vapor artery 15.0 mm (0.59 inch) in diameter
- A 0.25 mm (0.010 inch) monogroove slot connected the arteries and provided the capillary pumping force
- Circumferential wall grooves were cut in the vapor artery to ensure a wetted surface for evaporation and to drain liquid in the condenser
- Ammonia was the working fluid

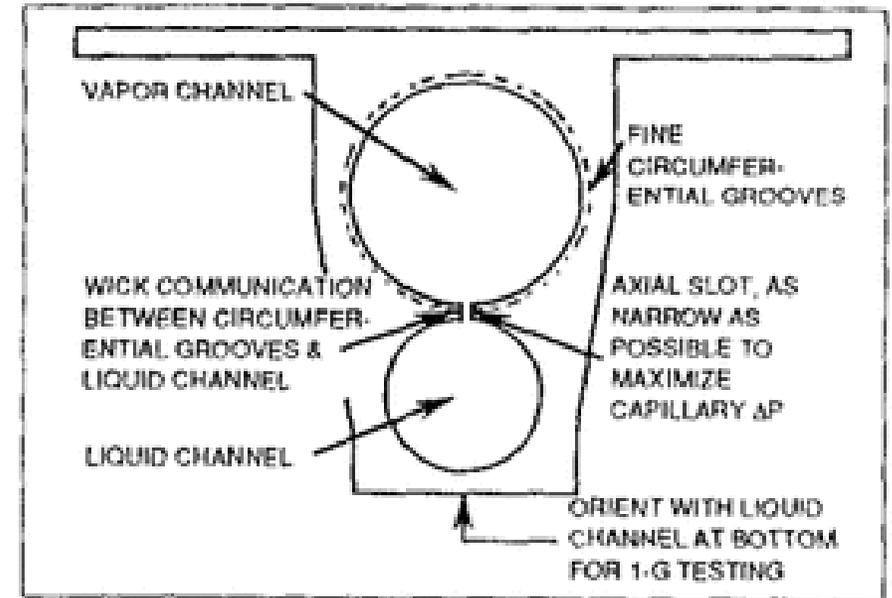


Fig. 1 Monogroove High Performance Heat Pipe

from: "Space Station Heat Pipe Advanced Radiator Element (SHARE) Flight Test Results and Analysis", R. Kosson, R. Brown, and E. K. Ungar, presented at 28th AIAA Aerospace Sciences Meeting, Reno, NV, January 1990, AIAA-90-0059

# The SHARE Heat Pipe

- A rigorous ground and flight test program was conducted to gain confidence that the arterial heat pipe would operate as expected in 0-g
- There were concerns about heat pipe priming – the liquid fill that occurs prior to startup
  - In 0-g, liquid will tend to fill the spaces with the smallest capillary diameters first
  - There was concern that since the monogroove slot had the smallest capillary dimension it would fill prematurely during priming and would trap a vapor bubble in the artery

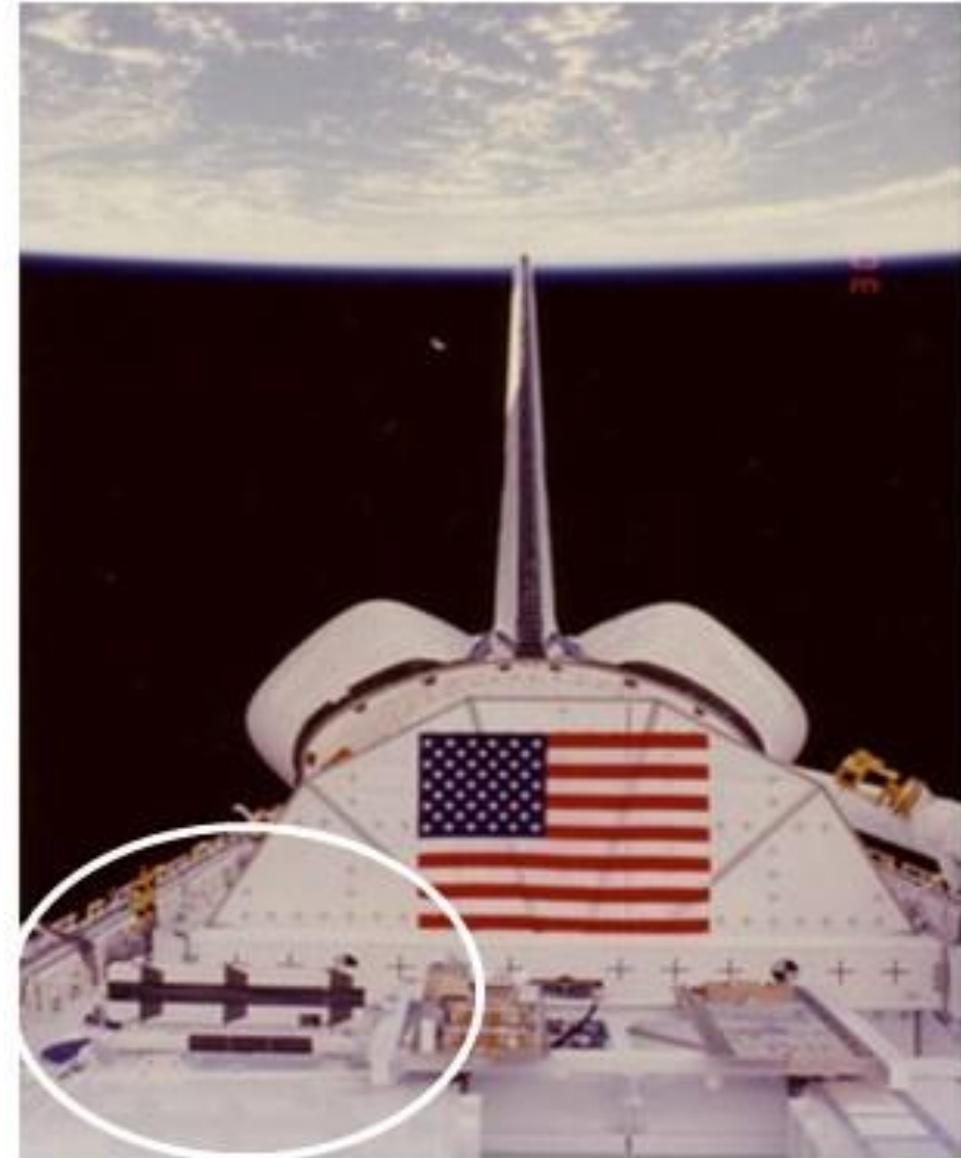
# The SHARE Heat Pipe

- Free-floating priming tests were performed on the KC-135 reduced gravity aircraft using an ammonia-filled heat pipe section
- A glass side wall allowed for flow visualization
- The tests were successful – starting from an initial condition of equal levels in the liquid and vapor arteries, the liquid artery filled completely in 0-g



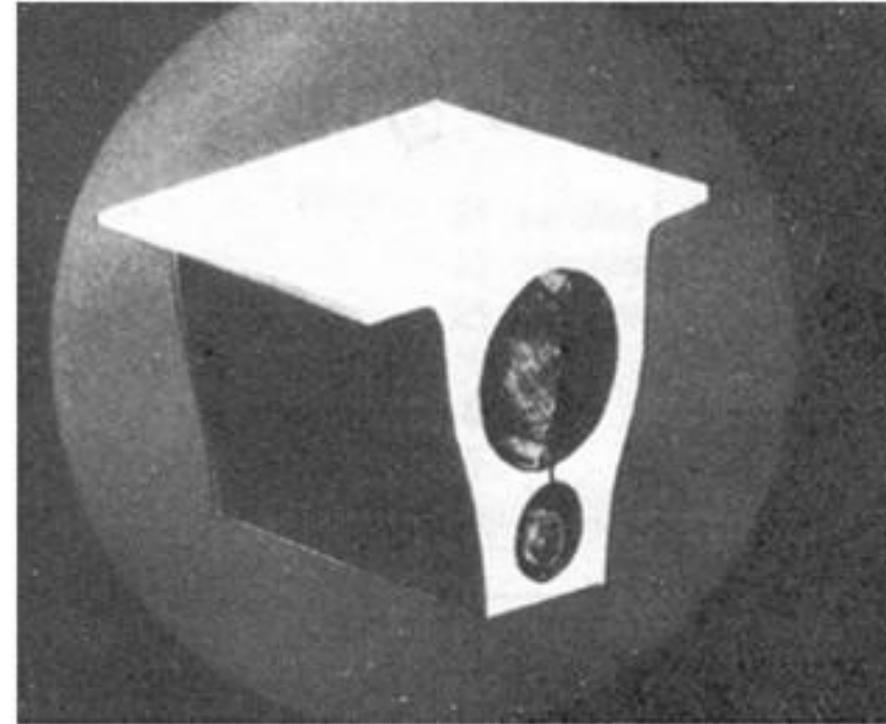
# The SHARE Heat Pipe

- A flight test was performed on STS-8 using a short U-shaped length of extrusion charged with Freon-21
- The heat pipe primed, started and operated successfully under an electric heat load



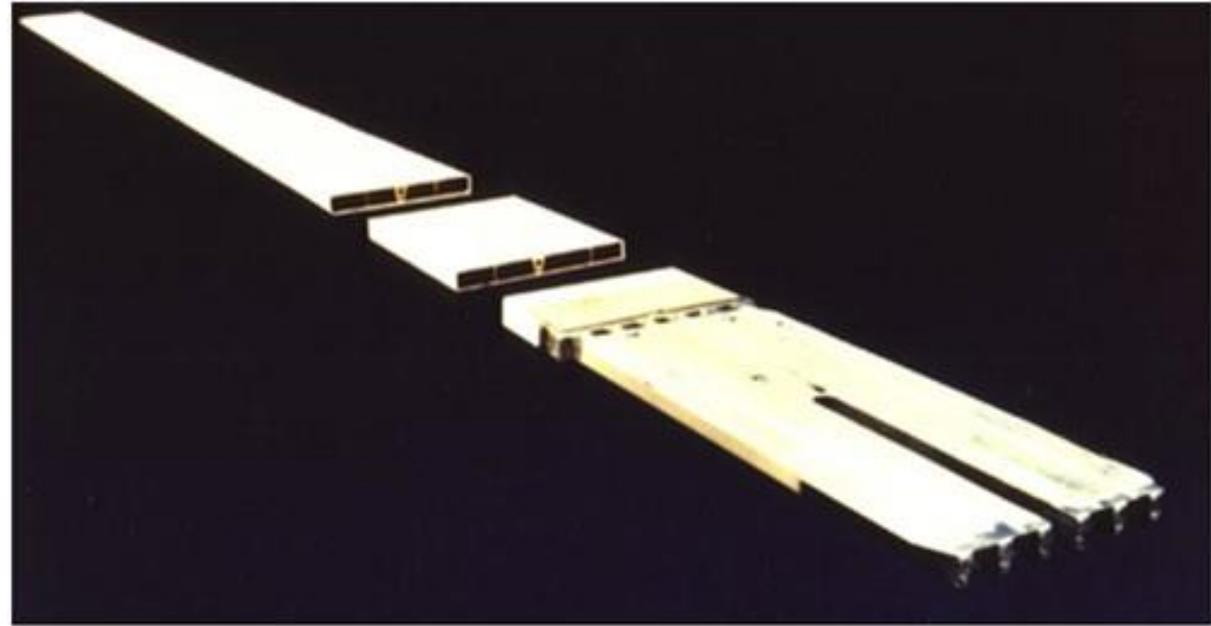
# The SHARE Heat Pipe

- Following the successful STS-8 flight test, three improvements were made to the design,
  - the extrusion cross-section was optimized to reduce heat transfer that might cause boiling in the liquid artery
  - a bridging wick was added to the evaporator section vapor artery to enhance liquid transport to the top of the extrusion where evaporation occurred
  - a screen core was added in the evaporator liquid artery to enhance liquid feed



# The SHARE Heat Pipe

- The new heat pipe extrusion was integrated into a multiple evaporator heat pipe 15.2 m (50 ft) long
- The heat pipe consisted of six identical parallel evaporator legs connected by a 90 degree manifold to a single condenser leg
- The evaporator, condenser, and manifold were all constructed from the improved heat pipe extrusion



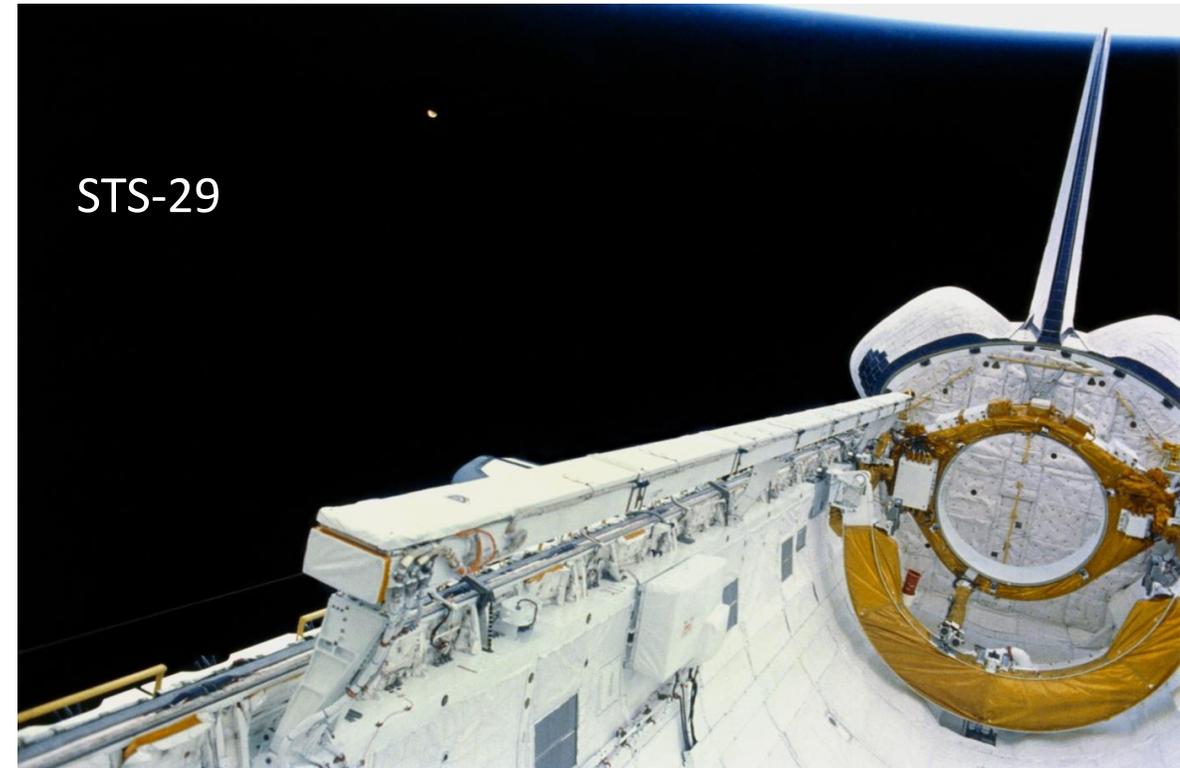
Prototypic Space Station Heat Pipe Radiator ORU

# The SHARE Heat Pipe

- 2kW heat transport capacity (600,000 W-in vs. ~10,000 W-in axial groove limit)
- Electrical resistance heaters provided the heat load
- The heat pipe was ground tested at an adverse tilt in thermal vacuum
  - Adverse tilt is the condition where the evaporator is elevated slightly compared to the condenser
  - Testing in this way drains excess liquid to the condenser and forces the heat pipe to work against gravity
  - Maximum capillary pumping capability at ambient temperature (ammonia working fluid) was 1.3 inches (33 mm)
- The ground tests were successful and the heat pipe met performance predictions

# The SHARE Heat Pipe

- The Space Station Heat Pipe Advanced Radiator Element (SHARE) flew on STS-29 in March 1989
- The heat pipe was mounted on the Orbiter's starboard longeron



# The SHARE Heat Pipe

- After 24 hours on-orbit, the evaporator was powered up and dried out almost immediately
  - Multiple priming attempts were made by firing the Orbiter's attitude control thrusters to move all the liquid into the condenser and allowing the heat pipe to passively re-prime
  - The Orbiter was also tumbled in an attempt to fill the evaporator with liquid
- The problem was identified real-time as a combination of
  - non-self-priming manifold,
  - evaporator hydraulic diameter mismatch

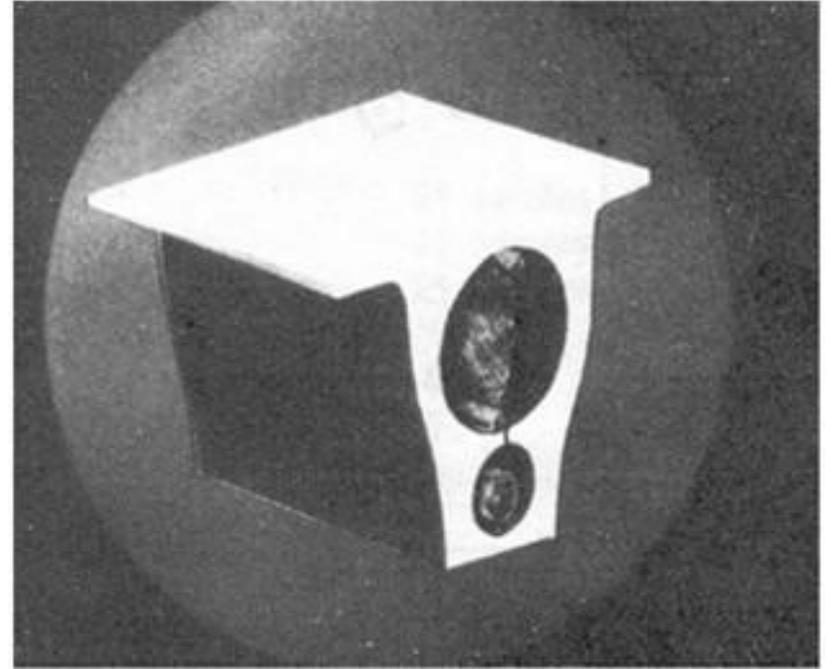


# The SHARE Heat Pipe

- Manifold priming
  - the 1-g tests had to start with a primed heat pipe
    - the 0.400" diameter liquid channel had a static wicking height of 0.030"
  - manifold priming could not be tested on the ground
    - after we'd seen the phenomena it was "obvious"

# The SHARE Heat Pipe

- The evaporator diameter was 0.590"
  - with the vertical screen wick, the hydraulic diameter was reduced to 0.360", which was 10% less than the liquid channel diameter of 0.400"
- Liquid will always preferentially wet from smallest space to largest space
  - monogroove – 0.51 mm (0.020 inch)
  - evaporator liquid passage – 5.1 mm (0.20 inch) (including the screen wick)
  - evaporator vapor passage – 9.1 mm (0.36 inch) (including the bridging wick)
  - condenser liquid passage – 10.2 mm (0.40 inch)
  - condenser vapor passage – 15.0 mm (0.59 inch)



# The SHARE Heat Pipe

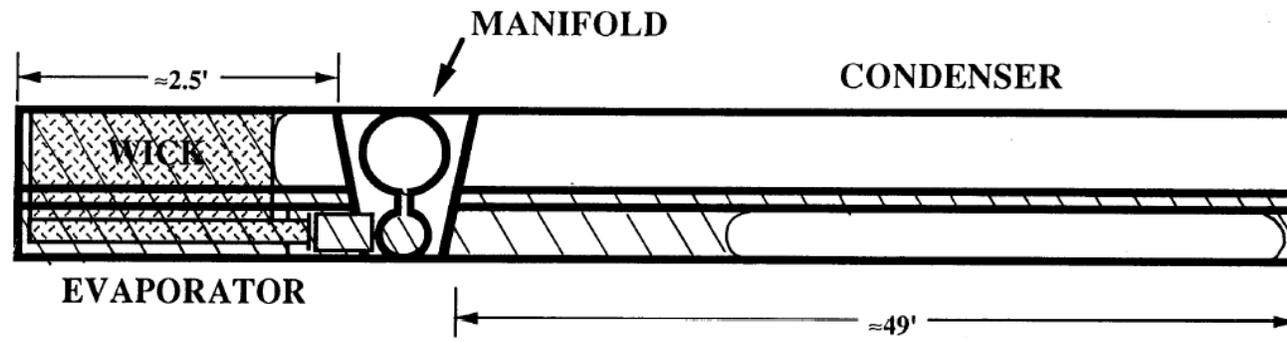
- Once the liquid distribution in the unpowered heat pipe had relaxed to its natural 0-g state, the liquid filled the monogroove, the liquid passages in the evaporator and the vapor passages in the evaporator
- The remainder of the liquid resided in the condenser liquid artery
- Since the liquid charge was sized to fill only the liquid artery, the lack of available liquid left a large vapor bubble in the liquid artery
- Once heat was applied, liquid evaporated until the large vapor bubble reached the evaporator – then the heat pipe would dry out and deprime

# The SHARE Heat Pipe

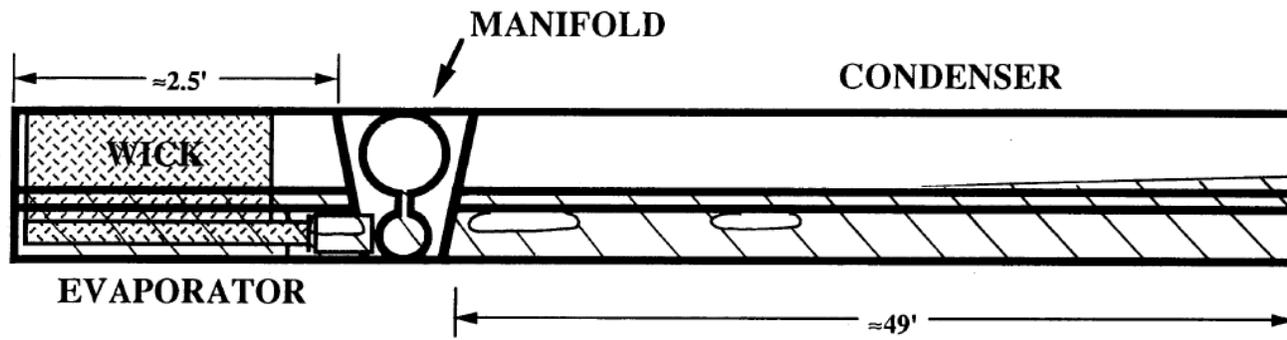
- Two issues:
  - non-self-priming manifold,
  - evaporator hydraulic diameter mismatch
- Had there only been one of the issues the heat pipe would probably have worked
  - with a priming manifold, the evaporator could have been dried out and allowed to rewet – then the heat pipe could have been started
  - with no evaporator wick, the liquid would have eventually migrated to the liquid side and the heat pipe would have operated
- In fact, it was fortuitous that both problems were present, otherwise a false positive result could have occurred

# The SHARE Heat Pipe

- Attempts at repriming the heat pipe were unsuccessful because of the non-priming manifold
- Starting from equal liquid levels in in the condenser liquid and vapor arteries, the liquid front would advance in the smaller hydraulic diameter liquid artery towards the manifold
- Once it reached the manifold, the artery opened into the perpendicular passage
- To the priming front, this was a large volume whose hydraulic diameter was effectively infinite - the priming stopped



COMMENTS: 0-g FLOODED EVAPORATOR

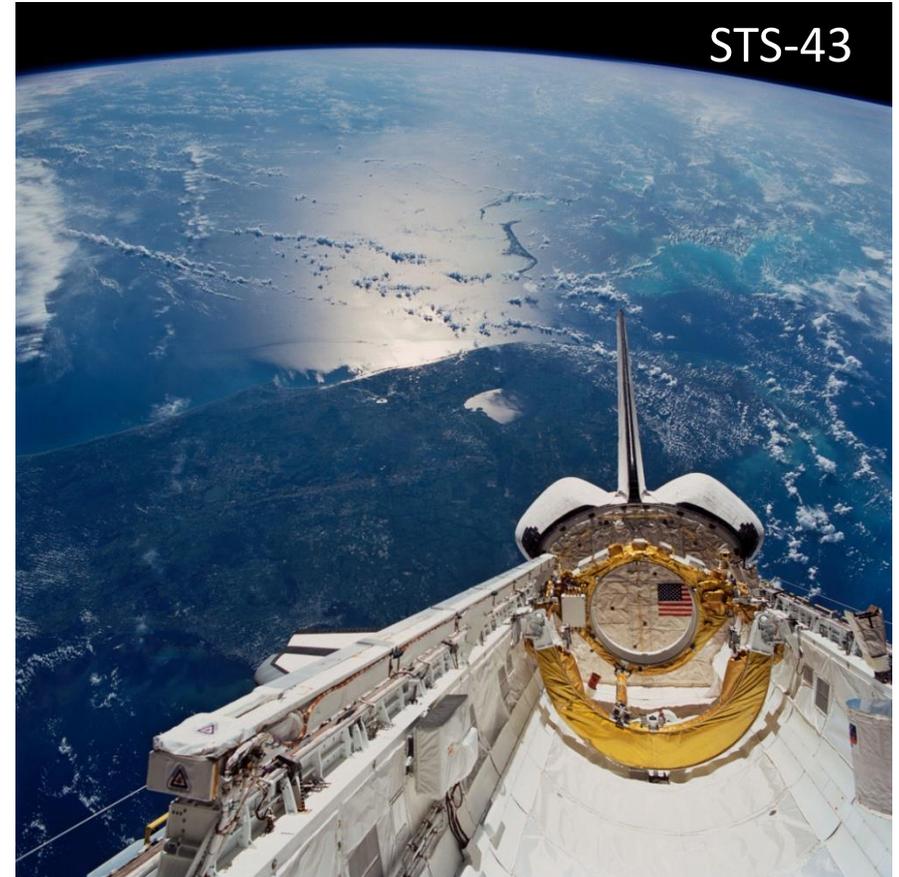


Bond number = 1,  $h=0.16$  inches  
(4.1 mm)

COMMENTS: 1-g VAPOR BUBBLES

# The SHARE Heat Pipe

- Neither of the key design faults were evident in ground testing
  - Gravity kept the evaporator vapor passage dry and allowed the manifold to prime when the heat pipe was horizontal
  - Gravity overwhelmed the surface tension forces that governed the 0-g behavior
- Once these faults were understood, a redesign was implemented
- The evaporator and manifold design faults were remedied and the follow on SHARE2 flight experiment on STS-43 was fully successful



# 0-g Will Fool You

## Summary

- Capillary forces are subtle and will often be overwhelmed by gravity in 1-g tests
- A great deal of care must be taken to ensure that ground tests of capillary systems are conducted properly and that their results are interpreted correctly

# SHARE Lessons Learned

The SHARE experience shows that even a robust ground and subscale flight test program might not be sufficient to uncover the subtle forces at work in 0-g

1. Test as you fly – fly as you test: The KC-135 and STS-8 tests did not include a manifold, so the non-priming manifold issue was not uncovered - in addition, the bridging wick that was added after these tests was a key contributor to the behavior seen on STS 29
2. Calculations can illuminate: Performing the hydraulic diameter calculations after adding the bridging wick would have uncovered the hydraulic diameter mismatch – these calculations were not performed until during STS-29
3. Sometimes you have to be the fluid: The manifold priming issue was only understood when the engineers thought like the priming fluid – filling the smaller hydraulic diameter vapor artery until reaching the relative vastness of the perpendicular manifold

Questions?

# Gravity-Insensitive Two-Phase Systems

- Gravity-insensitive two-phase systems are a robust choice for 0-g applications because they do not require expensive reduced gravity testing
- There are two types of gravity-insensitive conditions
  - Surface tension dominated (vs. buoyancy dominated)
  - Inertia dominated (vs. buoyancy dominated)
- Surface tension dominated - Bond number dependence

$$Bo = \frac{g L^2 (\rho_f - \rho_g)}{\sigma}$$

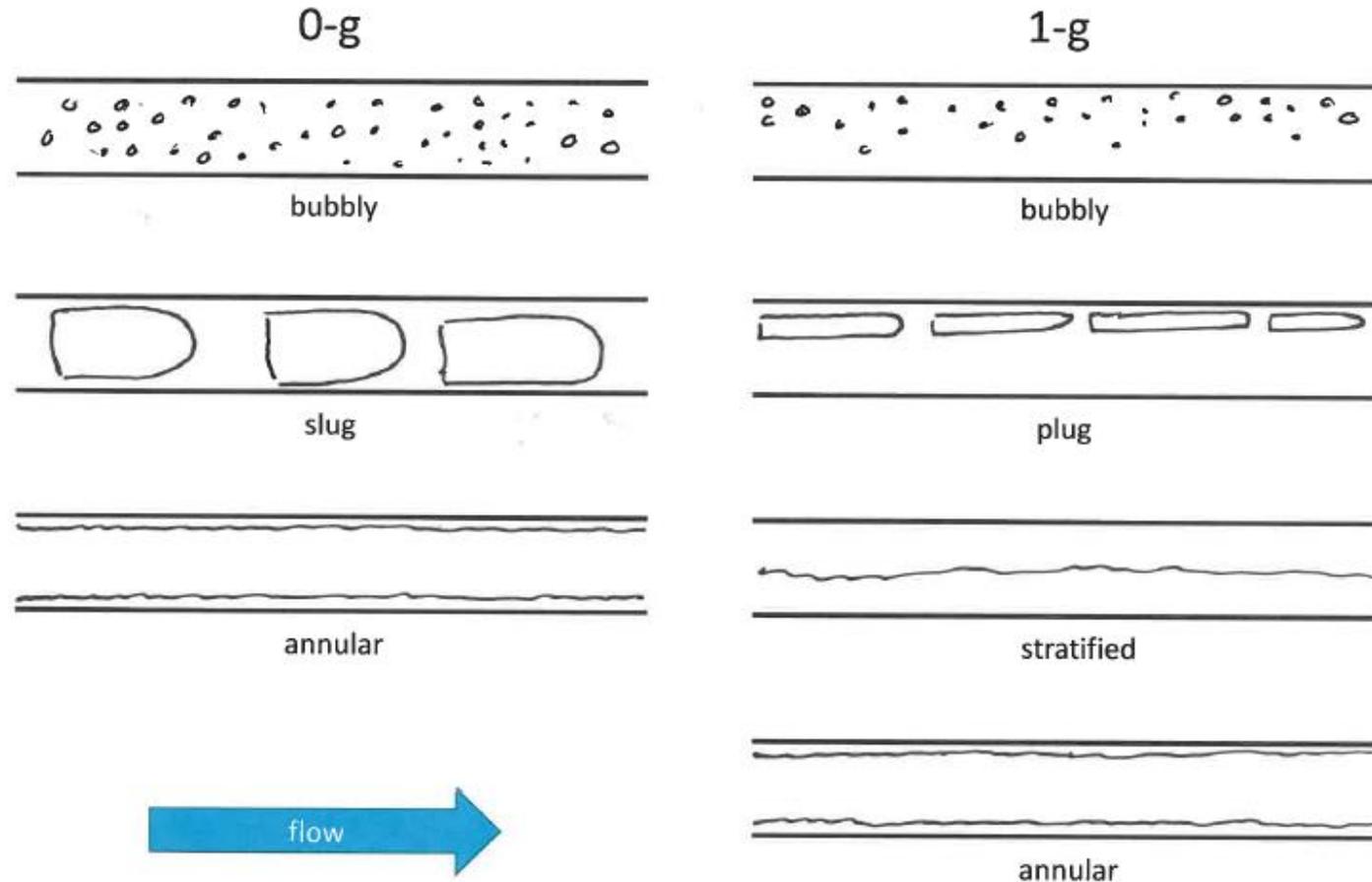
$$h \leq 2 \sqrt{\frac{\sigma}{g(\rho_f - \rho_g)}}$$

- Capillary devices must be very small to be gravity insensitive
- Meeting the Bond number requirement generally makes them too small to be of practical use

# Gravity-Insensitive Two-Phase Systems

- A better option is to use inertia dominated mechanically pumped systems
- A truly gravity-insensitive pumped two-phase system would have the same conditions in 0-g and 1-g
- The flow behavior and pressure drop would be identical

# Two – Phase Flow Regimes in 0-g and 1-g (horizontal tube)

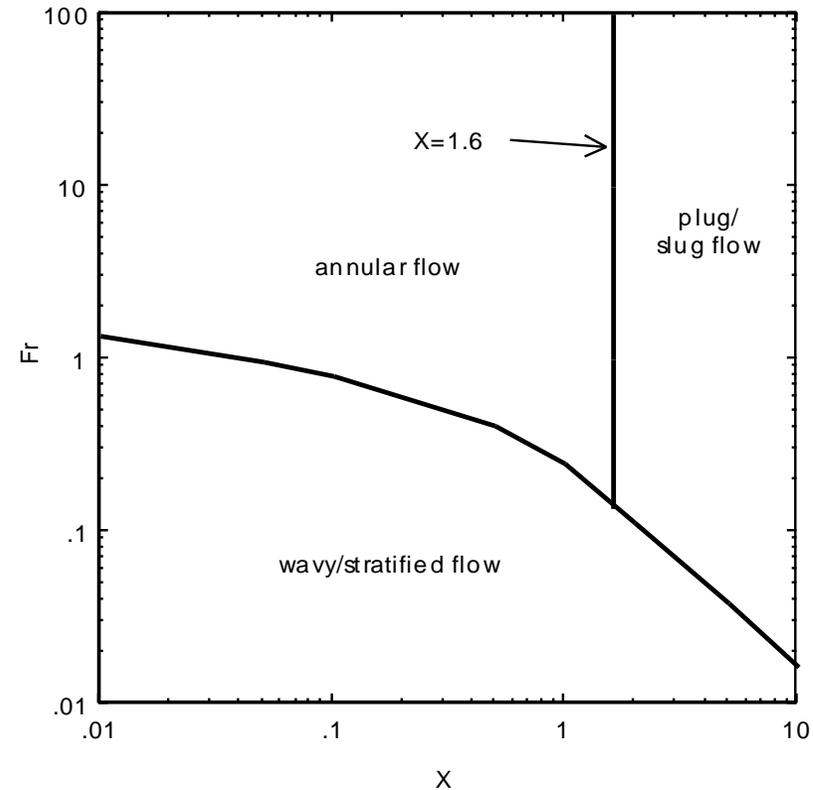


# Gravity-Insensitive Two-Phase Systems

- Typical horizontal tube flow regimes in 1-g are bubbly, plug, stratified, and annular - all are non-axisymmetric except for annular flow
- In 0-g all the flow regimes are axisymmetric
  - The bubbles in bubbly flow become evenly distributed
  - Plug bubbles expand to fill the tube diameter
  - stratified flows become annular with a thick liquid layer
  - But annular flows are very much the same in 1-g and 0-g
- We usually think of gravity-insensitive systems as those that operate the same in any orientation, but this can be relaxed somewhat for two-phase systems
- By keeping the parts of the system with two-phase flow horizontal and limiting or eliminating changes in elevation, gravity-independence is easier to obtain
- By testing the system in a flat horizontal configuration, the flow only has to overcome gravity over the height – not over the length of the system

# Gravity-Insensitive Two-Phase Systems

- The check for gravity independence requires assessing the flow regime
- The flow must be annular to be gravity independent



**Partial Flow Regime Map for Horizontal Tubes**

from: "A Model for Predicting Flow Regime Transitions in Horizontal and Near Horizontal Gas-Liquid Flow",  
Yemada Taitel and A. E. Dukler, AIChE Journal, January 1976

# Gravity-Insensitive Two-Phase Systems

- X is the Martinelli parameter which is widely used in the prediction of two-phase flow

$$X = \left( \frac{(dp/dz)_{sf}}{(dp/dz)_{sg}} \right)^{1/2}$$

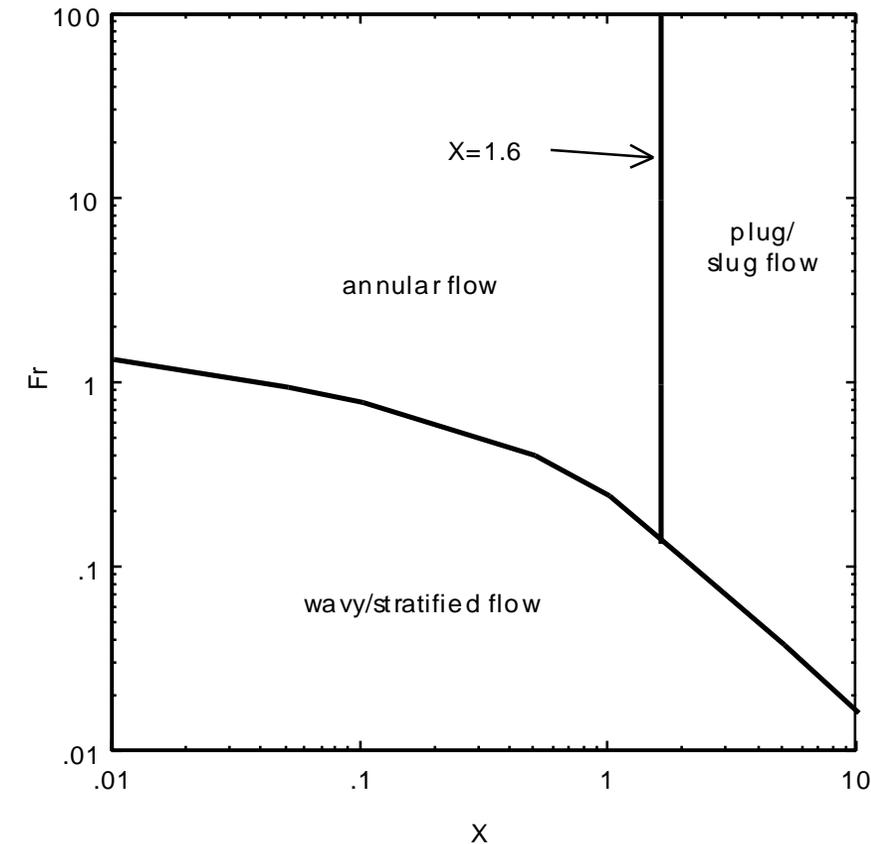
- where  $(dp/dz)_{sf}$  is the frictional pressure gradient if the liquid were flowing alone in the tube
- and  $(dp/dz)_{sg}$  is the frictional pressure gradient if the vapor were flowing alone in the tube
- The Martinelli parameter can be thought of as the degree of “liquidness” of the flow
  - It is large for flows that are mostly liquid and small for those that are mostly vapor

# Gravity-Insensitive Two-Phase Systems

- The modified Froude number also appears in the flow regime map

$$Fr = \sqrt{\frac{\rho_g}{\rho_f - \rho_g} \frac{u_{sg}}{\sqrt{dg}}}$$

- where  $\rho_f$  and  $\rho_g$  are the liquid and vapor densities, respectively,
- $u_{sg}$  is the velocity of the vapor if it were flowing alone in the tube
- The modified Froude number is the ratio of inertia forces to buoyancy forces
- The flow map shows that annular flow does not exist for  $X > 1.6$  and that  $Fr = 1$  is the approximate boundary between annular flow and wavy/stratified flow



Partial Flow Regime Map for Horizontal Tubes

# Gravity-Insensitive Two-Phase Systems

- For the flow to be 0-g-like in 1-g,  $X < 1.6$  and  $Fr > 1$
- If both of these conditions are met, a horizontal ground test will give results similar to the 0-g case
- It should be noted that these limits are fuzzy boundaries – the farther away from the limit, the more 0-g-like the behavior will be

# Scaling of Two-Phase Flows

- If a two-phase system is not gravity-insensitive, careful consideration must be given to the 0-g two-phase behavior and how it differs from behavior on the ground
- Microgravity testing may be required to gain confidence in the design
  - Reduced gravity aircraft testing offers only about 20 seconds of low gravity and requires the use of non-toxic fluids
    - Testing is typically limited to components or scaled test articles
  - When testing on a spacecraft, 0-g time is unlimited, but toxicity, volume, and power limitations generally require that the tests be scaled
    - Scaling two-phase flows is more complicated than scaling single phase flows, but can be done using dimensionless groups
    - For single phase flows it is sufficient to match the geometry and the Reynolds number – two-phase flows require more groups

# Buckingham Pi Theorum

A physical relationship among  $n$  variables, which can be expressed in a minimum of  $m$  dimensions can be rearranged into a relationship among  $(n-m)$  *independent* dimensionless groups of the original variables

- Gives us a method to both determine the minimum number of *independent* dimensionless groups that must be satisfied for similarity

# Buckingham Pi Theorum

- In adiabatic component 0-g two-phase flow in a tube, the frictional pressure gradient,  $dp/dz$ , is expressed in Pa/m and is a function of only the following independent variables

➤	$d$	tube inner diameter	(m)
➤	$\rho_f$	liquid density	(kg/m <sup>3</sup> )
➤	$\rho_g$	vapor density	(kg/m <sup>3</sup> )
➤	$\mu_f$	liquid viscosity	(kg/ms)
➤	$\mu_g$	vapor viscosity	(kg/ms)
➤	$\sigma$	fluid surface tension	(N/m)
➤	$u_{sf}$	superficial liquid velocity (velocity of the liquid flowing alone)	(m/s)
➤	$u_{sg}$	superficial vapor velocity (velocity of the vapor flowing alone)	(m/s)

- This is the minimum number of variables - other two-phase flow variables such as mass flow rate and vapor quality are simple functions of the variables in the list

# Buckingham Pi Theorem

- In this case, there are 9 variables,  $dp/dz$ ,  $d$ ,  $\rho_f$ ,  $\rho_g$ ,  $\mu_f$ ,  $\mu_g$ ,  $\sigma$ ,  $u_{sf}$ , and  $u_{sg}$
- They are expressed in a minimum of three dimensions (kg, m, and s)
  - N can be expressed as  $\text{kg m/s}^2$  and Pa can be expressed as  $\text{N/m}^2$  or  $\text{kg/ms}^2$
- This yields 6 dimensionless groups per Buckingham's Pi Theorem
- One possible independent list of these groups is:

# Buckingham Pi Theorum

$$\Phi_g^2 = \text{fn} \left( \frac{Q_f}{Q_g}, \text{Re}_g, \text{Re}_f, \text{We}_g, \text{We}_f \right)$$

the subscripts f and g refer to the liquid and vapor phases, respectively

where:

$$\Phi_g^2 = \frac{\left. \frac{dp}{dz} \right|_{sg}}{f_{sg} \frac{1}{d} \frac{1}{2} Q_g u_{sg}^2}$$

the ratio of the pressure gradient if the vapor were flowing alone to the pressure gradient if the vapor were flowing alone

$f_{sg}$  is the Darcy friction factor of the vapor flowing alone in the tube

# Buckingham Pi Theorum

- where:

$$\rho_f/\rho_g$$

the density ratio – the ratio of the liquid and vapor densities

$$\text{Re}_g = \frac{\rho_g u_{sg} d}{\mu_g}$$

the vapor Reynolds number

$$\text{Re}_f = \frac{\rho_f u_{sf} d}{\mu_f}$$

the liquid Reynolds number

# Buckingham Pi Theorem

- where:

$$We_g = \frac{\rho_g u_{sg}^2 d}{\sigma} \quad \text{the vapor Weber number}$$

$$We_f = \frac{\rho_f u_{sf}^2 d}{\sigma} \quad \text{the liquid Weber number}$$

The Reynolds numbers are the ratio of inertial to viscous forces  
The Weber numbers are the ratios of inertial forces to surface tension forces

# Buckingham Pi Theorem

- Alternately, one of the independent dimensionless groups can be replaced with the well known Martinelli parameter,  $X$

$$X = \frac{\left(\frac{dp}{dz}\Big|_{sf}\right)^2}{\left(\frac{dp}{dz}\Big|_{sg}\right)^2}$$

can be thought of as a measure of the “liquidness” of the flow

- This yields an alternate valid list of independent dimensionless groups which has the same validity

$$\Phi_g^2 = \text{fn} \left( \frac{Q_f}{Q_g}, \text{Re}_g, \text{Re}_f, \text{We}_g, X \right)$$

# Buckingham Pi Theorem

- The 0-g flow regime can be expressed as a function of the same five independent dimensionless groups

$$\text{flow regime} = \text{fn} \left( \frac{Q_f}{Q_g}, \text{Re}_g, \text{Re}_f, \text{We}_g, X \right)$$

# Buckingham Pi Theorem

- For 0-g two phase flow in a straight tube, if we match
  - density ratio
  - liquid and vapor Reynolds numbers
  - vapor Weber number
  - Martinelli parameter

we meet the conditions of similarity

- The flow regimes and two-phase frictional multipliers will be identical

# Similarity

- For a scaled 0-g two-phase system, one-to-one correspondence is obtained if the systems are geometrically similar and the five independent dimensionless groups are matched
- The flow regimes and two-phase frictional multipliers of the systems will be identical
- In a real case, it is impossible to match all five exactly
  - One strategy
    - Match  $Re_g$
    - $Re_f$  laminar or turbulent as appropriate
    - Get close on  $\rho_f/\rho_g$
    - Match  $X$  as well as possible

# Buckingham Pi Theorem

- For lunar and Martian applications, gravity is an additional independent variable
- Results in an additional dimensionless group, the modified Froude number

$$Fr = \sqrt{\frac{\rho_g}{\rho_f - \rho_g} \frac{u_{sg}}{\sqrt{dg}}}$$

# Scaling Summary

- In 0-g

$$\Phi_g^2 = \text{fn} \left( \frac{Q_f}{Q_g}, Re_g, Re_f, We_g, X \right)$$

$$\text{flow regime} = \text{fn} \left( \frac{Q_f}{Q_g}, Re_g, Re_f, We_g, X \right)$$

- In partial g

$$\Phi_g^2 = \text{fn} \left( \frac{Q_f}{Q_g}, Re_g, Re_f, We_g, X, Fr \right)$$

$$\text{flow regime} = \text{fn} \left( \frac{Q_f}{Q_g}, Re_g, Re_f, We_g, X, Fr \right)$$

Questions?

# Building Two-Phase Systems for Zero-Gravity

- Try to scale to a gravity independent system
- May need a small 0-g experiment as a convincer, but that will be scaled too
  - 0-g time and expense are proportional to a power  $\gg 1$
  - Choose a method and schedule that allows for failure if possible
- Remember, you are scaling once you go to a flight experiment, so there is no reason not to try to scale to gravity independence

# The Need for Partial Gravity Testing

- In the Buckingham Pi analysis, gravity is just another variable
- If you test in a partial gravity aircraft, you are almost invariably
  - Testing a subscale unit
    - To reduce the transport time to less than the reduced gravity time
    - To fit on the plane
  - Testing with a different fluid
    - For safety
    - For scaling reasons
- So you are already scaling the system
- There is no need at all to test in partial gravity – it's the dimensionless groups that must match, not a single parameter
- If you are testing a partial gravity system, try to do your testing in 1-g and scale accordingly (hyper gravity is also an option)

# Summary

- Even though two-phase behavior can differ greatly between 1-g and 0-g, there are approaches that allow us to understand the behavior and minimize the differences in some cases
- The airflow-induced movement of liquid drops attached to surfaces in 0-g is difficult
  - It can be predicted from basic principles by calculating the forces involved
- Gravity insensitive two-phase systems can be specified - either pumped systems that are inertia dominated or physically small systems that are surface tension dominated
  - Pumped inertia dominated systems with horizontal two-phase sections can be ground tested and their behavior will be the same in 1-g as in 0-g
    - However, the testing is only 1:1 when gravity-insensitive annular flow is present
  - Surface tension dominated systems can also be used, but these systems must be dimensionally small for surface tension to dominate in 1 g
    - Their small size may make them impracticable

# Summary

- If a two-phase system is chosen that is sensitive to gravity level, careful consideration must be given to the 0-g two-phase behavior and how it differs from testing on the ground
- Microgravity testing may be required to gain confidence in the design
- The limited time available on reduced gravity aircraft and toxicity concerns may limit testing to the component level and will likely require scaling
- If testing on a spacecraft, unlimited 0-g is available, but toxicity, volume, and power limitations usually require that the tests be scaled by matching geometry and five dimensionless groups
- Even with careful 1-g and reduced gravity component or scaled system testing, two-phase systems will often surprise us with their 0 g behavior
- To minimize surprises, it's important to understand the forces at work on the ground and in reduced gravity scaled testing, and how they relate to the 0-g case
- Partially gravity testing is useful only for full scale systems with very short time constants

# Conclusion

- The lack of gravity often makes two-phase behavior very different in 0-g than in 1-g
- Being aware of the different forces at work allows a better understanding of the different behaviors
- Zero-g systems can be designed to be fully ground testable, but this can greatly constrain system design
- Systems that are not fully ground testable must be attacked by a combination of physical understanding, calculations, and careful testing